EE 330
Lecture 25

• Small Signal Analysis
  – SS Models for MOSFET
  – SS Models for BJT
Exam 2  Friday March  9

Exam 3  Friday April  13

Review Session for Exam 2:
6:00 p.m. on Thursday March 8 in Room Sweeney 1116
Review from Last Lecture

Small-signal and simplified dc equivalent elements

<table>
<thead>
<tr>
<th>Element</th>
<th>ss equivalent</th>
<th>Simplified dc equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>dc Voltage Source</td>
<td>$V_{DC}$</td>
<td>$V_{DC}$</td>
</tr>
<tr>
<td>ac Voltage Source</td>
<td>$V_{AC}$</td>
<td>$V_{AC}$</td>
</tr>
<tr>
<td>dc Current Source</td>
<td>$I_{DC}$</td>
<td>$I_{DC}$</td>
</tr>
<tr>
<td>ac Current Source</td>
<td>$I_{AC}$</td>
<td>$I_{AC}$</td>
</tr>
<tr>
<td>Resistor</td>
<td>$R$</td>
<td>$R$</td>
</tr>
</tbody>
</table>

Element symbols:
- **dc Voltage Source**: $V_{DC}$
- **ac Voltage Source**: $V_{AC}$
- **dc Current Source**: $I_{DC}$
- **ac Current Source**: $I_{AC}$
- **Resistor**: $R$
Review from Last Lecture

Small-signal and simplified dc equivalent elements

<table>
<thead>
<tr>
<th>Element</th>
<th>ss equivalent</th>
<th>Simplified dc equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOSFET</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(enhancement or depletion)</td>
<td></td>
<td>Simplified</td>
</tr>
<tr>
<td>JFET</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diodes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simplified</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Review from Last Lecture

Small-signal and simplified dc equivalent elements

<table>
<thead>
<tr>
<th>Element</th>
<th>ss equivalent</th>
<th>Simplified dc equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bipolar Transistors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dependent Sources (Linear)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- $V_O = A_V V_{IN}$  
  $I_O = A_I I_{IN}$
- $V_O = R_T I_{IN}$  
  $I_O = G_T V_{IN}$
Small-Signal Model of BJT and MOSFET

Consider 4-terminal network

\[
\begin{align*}
I_1 &= f_1(V_1, V_2, V_3) \\
I_2 &= f_2(V_1, V_2, V_3) \\
I_3 &= f_3(V_1, V_2, V_3)
\end{align*}
\]

Define

\[
\begin{align*}
i_1 &= I_1 - I_{1Q} \\
i_2 &= I_2 - I_{2Q} \\
i_3 &= I_3 - I_{3Q} \\
u_1 &= V_1 - V_{1Q} \\
u_2 &= V_2 - V_{2Q} \\
u_3 &= V_3 - V_{3Q}
\end{align*}
\]

Small signal model is that which represents the relationship between the small signal voltages and the small signal currents.
Nonlinear Model
\[ I_1 = f_1(V_1, V_2, V_3) \quad \Rightarrow \quad i_1 = y_{11}v_1 + y_{12}v_2 + y_{13}v_3 \]
\[ I_2 = f_2(V_1, V_2, V_3) \quad \Rightarrow \quad i_2 = y_{21}v_1 + y_{22}v_2 + y_{23}v_3 \]
\[ I_3 = f_3(V_1, V_2, V_3) \quad \Rightarrow \quad i_3 = y_{31}v_1 + y_{32}v_2 + y_{33}v_3 \]

where
\[ y_{ij} = \left. \frac{\partial f_i(V_1, V_2, V_3)}{\partial V_j} \right|_{V=V_Q} \]
Small-Signal Model

\[ i_1 = y_{11} v_1 + y_{12} v_2 + y_{13} v_3 \]
\[ i_2 = y_{21} v_1 + y_{22} v_2 + y_{23} v_3 \]
\[ i_3 = y_{31} v_1 + y_{32} v_2 + y_{33} v_3 \]

where

\[ y_{ij} = \left. \frac{\partial f_i(V_1, V_2, V_3)}{\partial V_j} \right|_{V=\bar{V}_Q} \]

- This is a small-signal model of a 4-terminal network and it is linear
- 9 small-signal parameters characterize the linear 4-terminal network
- Small-signal model parameters dependent upon Q-point
- Termed the y-parameter model or “admittance” – parameter model
Review from Last Lecture

### 4-terminal small-signal network summary

\[
\begin{align*}
I_1 &= f_1(V_1, V_2, V_3) \\
I_2 &= f_2(V_1, V_2, V_3) \\
I_3 &= f_3(V_1, V_2, V_3)
\end{align*}
\]

Small signal model:

\[
\begin{align*}
i_1 &= y_{11}v_1 + y_{12}v_2 + y_{13}v_3 \\
i_2 &= y_{21}v_1 + y_{22}v_2 + y_{23}v_3 \\
i_3 &= y_{31}v_1 + y_{32}v_2 + y_{33}v_3
\end{align*}
\]

\[
y_{ij} = \left. \frac{\partial f_i(V_1, V_2, V_3)}{\partial V_j} \right|_{V=V_Q}
\]
Small-Signal Model

\[ i_1 = g_1(v_1, v_2, v_3) \]
\[ i_2 = g_2(v_1, v_2, v_3) \]
\[ i_3 = g_3(v_1, v_2, v_3) \]

\[ i_1 = y_{11}v_1 + y_{12}v_2 + y_{13}v_3 \]
\[ i_2 = y_{21}v_1 + y_{22}v_2 + y_{23}v_3 \]
\[ i_3 = y_{31}v_1 + y_{32}v_2 + y_{33}v_3 \]

\[ y_{ij} = \frac{\partial f_i(v_1, v_2, v_3)}{\partial v_j} \bigg|_{v_i = v_a} \]
MOSFET is actually a 4-terminal device but for many applications, acceptable predictions of performance can be obtained by treating it as a 3-terminal device by neglecting the bulk terminal.

In this course, we have been treating it as a 3-terminal device and in this lecture will develop the small-signal model by treating it as a 3-terminal device.

When treated as a 4-terminal device, the bulk voltage introduces one additional term to the small signal model which is often either negligibly small or has no effect on circuit performance (will develop 4-terminal ss model later).
Small Signal Model of MOSFET

Large Signal Model

\[ I_G = 0 \]

3-terminal device

\[
I_D = \begin{cases} 
0 & V_{GS} \leq V_T \\
\mu C_{OX} \frac{W}{L} \left( V_{GS} - V_T - \frac{V_{DS}}{2} \right) V_{DS} & V_{GS} \geq V_T, V_{DS} < V_{GS} - V_T \\
\mu C_{OX} \frac{W}{2L} \left( V_{GS} - V_T \right)^2 \left( 1 + \lambda V_{DS} \right) & V_{GS} \geq V_T, V_{DS} \geq V_{GS} - V_T 
\end{cases}
\]

MOSFET is usually operated in saturation region in linear applications where a small-signal model is needed so will develop the small-signal model in the saturation region
Small Signal Model of MOSFET

\[ I_1 = f_1(V_1, V_2) \quad \leftrightarrow \quad I_G = 0 \]

\[ I_2 = f_2(V_1, V_2) \quad \leftrightarrow \quad I_D = \mu C_{ox} \frac{W}{2L} (V_{GS} - V_T)^2 \left(1 + \lambda V_{DS}\right) \]

\[ I_G = f_1(V_{GS}, V_{DS}) \]

\[ I_D = f_2(V_{GS}, V_{DS}) \]

**Small-signal model:**

\[ y_{ij} = \frac{\partial f_i(V_1, V_2)}{\partial V_j} \bigg|_{v=v_Q} \]

\[ y_{11} = \frac{\partial I_G}{\partial V_{GS}} \bigg|_{v=v_Q} \]

\[ y_{12} = \frac{\partial I_G}{\partial V_{DS}} \bigg|_{v=v_Q} \]

\[ y_{21} = \frac{\partial I_D}{\partial V_{GS}} \bigg|_{v=v_Q} \]

\[ y_{22} = \frac{\partial I_D}{\partial V_{DS}} \bigg|_{v=v_Q} \]
Small Signal Model of MOSFET

\[ I_G = 0 \]

\[ I_D = \mu C_{OX} \frac{W}{2L} (V_{GS} - V_T)^2 (1 + \lambda V_{DS}) \]

Small-signal model:

\[ y_{11} = \left. \frac{\partial I_G}{\partial V_{GS}} \right|_{V = V_D} = ? \]

\[ y_{12} = \left. \frac{\partial I_G}{\partial V_{DS}} \right|_{V = V_D} = ? \]

\[ y_{21} = \left. \frac{\partial I_D}{\partial V_{GS}} \right|_{V = V_D} = ? \]

\[ y_{22} = \left. \frac{\partial I_D}{\partial V_{DS}} \right|_{V = V_D} = ? \]

Recall: termed the \( y \)-parameter model
Small Signal Model of MOSFET

\[ I_1 = f_1(V_1, V_2) \quad \leftrightarrow \quad I_G = 0 \]

\[ I_2 = f_2(V_1, V_2) \quad \leftrightarrow \quad I_D = \mu C_{ox} \frac{W}{2L} (V_{GS} - V_T)^2 (1 + \lambda V_{DS}) \]

**Small-signal model:**

\[ y_{11} = \left. \frac{\partial I_G}{\partial V_{GS}} \right|_{V = V_G} = 0 \quad y_{12} = \left. \frac{\partial I_G}{\partial V_{DS}} \right|_{V = V_G} = 0 \]

\[ y_{21} = \left. \frac{\partial I_D}{\partial V_{GS}} \right|_{V = V_G} = 2 \mu C_{ox} \frac{W}{2L} (V_{GS} - V_T)^2 (1 + \lambda V_{DS}) \left|_{V = V_G} = \mu C_{ox} \frac{W}{L} (V_{GS} - V_T) (1 + \lambda V_{DS}) \right. \]

\[ y_{21} \approx \mu C_{ox} \frac{W}{L} (V_{GS} - V_T) \]

\[ y_{22} = \left. \frac{\partial I_D}{\partial V_{DS}} \right|_{V = V_G} = \mu C_{ox} \frac{W}{2L} (V_{GS} - V_T)^2 \left|_{V = V_G} \approx \lambda I_{DOQ} \right. \]
Small Signal Model of MOSFET

\[ I_G = 0 \]

\[ I_D = \mu C_{ox} \frac{W}{2L} (V_{GS} - V_T)^2 (1 + \lambda V_{DS}) \]

\[ y_{12} = 0 \]
\[ y_{11} = 0 \]
\[ y_{21} \approx \mu C_{ox} \frac{W}{L} (V_{GSQ} - V_T) \]
\[ y_{22} \approx \lambda I_{DQ} \]

\[ i_G = y_{11} V_{GS} + y_{12} V_{DS} \]
\[ i_D = y_{21} V_{GS} + y_{22} V_{DS} \]

An equivalent circuit (y-parameter model)
Small-Signal Model of MOSFET

by convention, \( y_{21} = g_m \), \( y_{22} = g_0 \)

\[
\therefore \quad y_{21} \approx g_m = \mu C_{ox} \frac{W}{L} (V_{GSQ} - V_T)
\]

\[
y_{22} = g_0 \approx \lambda I_{DQ}
\]

Note: \( g_o \) vanishes when \( \lambda = 0 \)

still \( y \)-parameter model but use “\( g \)” parameter notation
Small-Signal Model of MOSFET

$$g_m = \mu C_{ox} \frac{W}{L} (V_{GSQ} - V_T)$$

$$g_o \approx \lambda I_{DQ}$$

Alternate equivalent expressions for $g_m$:

$$I_{DQ} = \mu C_{ox} \frac{W}{2L} (V_{GSQ} - V_T)^2 (1 + \lambda V_{DSQ}) \approx \mu C_{ox} \frac{W}{2L} (V_{GSQ} - V_T)^2$$

$$g_m = \mu C_{ox} \frac{W}{L} (V_{GSQ} - V_T)$$

$$g_m = \sqrt{2\mu C_{ox}} \frac{W}{L} \sqrt{I_{DQ}}$$

$$g_m = \frac{2I_{DQ}}{V_{GSQ} - V_T}$$
Consider again:

**Small-signal analysis example**

\[ v_{\text{IN}} = V_M \sin \omega t \]

\[ v_{\text{OUT}} = \frac{2I_{\text{DQ}} R}{\left[ V_{\text{SS}} + V_T \right]} \]

Derived for \( \lambda = 0 \)

\[ I_D = \mu C_{\text{ox}} \frac{W}{2L} \left( V_{\text{GS}} - V_T \right)^2 \]

Recall the derivation was very tedious and time consuming!
Consider again:

Small-signal analysis example

\[ A_v = \frac{V_{OUT}}{V_{IN}} = -\frac{g_m}{g_o + 1/R} \]

This gain is expressed in terms of small-signal model parameters

For \( \lambda = 0 \), \( g_o = \lambda I_{DQ} = 0 \)

\[ A_v = \frac{V_{OUT}}{V_{IN}} = -g_m R \]

but

\[ g_m = \frac{2I_{DQ}}{V_{GSQ} - V_T} \]

\[ V_{GSQ} = -V_{SS} \]

thus

\[ A_v = \frac{2I_{DQ} R}{V_{SS} + V_T} \]
Consider again:

**Small-signal analysis example**

\[
A_v = \frac{V_{OUT}}{V_{IN}} = -\frac{g_m}{g_o + 1/R}
\]

For \(\lambda=0\), \(g_O = \lambda I_{DQ} = 0\)

\[
A_v = \frac{2I_{DQ} R}{[V_{SS} + V_T]}
\]

Same expression as derived before

More accurate gain can be obtained if \(\lambda\) effects are included and does not significantly increase complexity of small-signal analysis.
Small Signal Model of BJT

3-terminal device

Forward Active Model:

\[
I_C = J_S A_E e^{V_{BE}/V_t} \left( 1 + \frac{V_{CE}}{V_{AF}} \right)
\]

\[
I_B = \frac{J_S A_E}{\beta} e^{V_{BE}/V_t}
\]

Usually operated in Forward Active Region when small-signal model is needed
Small Signal Model of BJT

**Nonlinear model:**

\[ I_1 = f_1 (V_1, V_2) \quad \iff \quad I_B = \frac{J_S A_E}{\beta} e^{\frac{V_{BE}}{V_t}} \]

\[ I_2 = f_2 (V_1, V_2) \quad \iff \quad I_C = J_S A_E e^{\frac{V_{BE}}{V_t}} \left( 1 + \frac{V_{CE}}{V_{AF}} \right) \]

**Small-signal model:**

\[ i_B = y_{11} V_{BE} + y_{12} V_{CE} \]

\[ i_C = y_{21} V_{BE} + y_{22} V_{CE} \]

\[ y_{ij} = \left. \frac{\partial f_i (V_1, V_2)}{\partial V_j} \right|_{V = V_Q} \]

\[ y_{11} = g_\pi = \left. \frac{\partial I_B}{\partial V_{BE}} \right|_{V = V_Q} \]

\[ y_{12} = \left. \frac{\partial I_B}{\partial V_{CE}} \right|_{V = V_Q} \]

\[ y_{21} = g_m = \left. \frac{\partial I_C}{\partial V_{BE}} \right|_{V = V_Q} \]

\[ y_{22} = g_o = \left. \frac{\partial I_C}{\partial V_{CE}} \right|_{V = V_Q} \]

Note: \( g_m, g_\pi \) and \( g_o \) used for notational consistency with legacy terminology
Small Signal Model of BJT

**Nonlinear model:**

\[ I_B = \frac{J_S A_E v_{BE}}{\beta} e^{\frac{v_{BE}}{V_t}} \]

\[ I_C = J_S A_E e^{\frac{v_{BE}}{V_t}} \left( 1 + \frac{V_{CE}}{V_{AF}} \right) \]

\[ i_B = y_{11} v_{BE} + y_{12} v_{CE} \]

\[ i_C = y_{21} v_{BE} + y_{22} v_{CE} \]

\[ y_{ij} = \left. \frac{\partial f_i (v_1, v_2)}{\partial v_j} \right|_{v = V_Q} \]

\[ y_{11} = g_x = \left. \frac{\partial I_B}{\partial v_{BE}} \right|_{v = V_Q} = ? \]

\[ y_{12} = \left. \frac{\partial I_B}{\partial v_{CE}} \right|_{v = V_Q} = ? \]

\[ y_{21} = g_m = \left. \frac{\partial I_C}{\partial v_{BE}} \right|_{v = V_Q} = ? \]

\[ y_{22} = g_o = \left. \frac{\partial I_C}{\partial v_{CE}} \right|_{v = V_Q} = ? \]

**Small-signal model:**

\[ y_{11} = g_x = \left. \frac{\partial I_B}{\partial v_{BE}} \right|_{v = V_Q} = ? \]

\[ y_{12} = \left. \frac{\partial I_B}{\partial v_{CE}} \right|_{v = V_Q} = ? \]

\[ y_{21} = g_m = \left. \frac{\partial I_C}{\partial v_{BE}} \right|_{v = V_Q} = ? \]

\[ y_{22} = g_o = \left. \frac{\partial I_C}{\partial v_{CE}} \right|_{v = V_Q} = ? \]
Small Signal Model of BJT

Nonlinear model:

Small-signal model:

\[ i_B = y_{11} V_{BE} + y_{12} V_{CE} \]

\[ i_C = y_{21} V_{BE} + y_{22} V_{CE} \]

\[
y_{11} = g_x = \left. \frac{\partial I_B}{\partial V_{BE}} \right|_{V = V_o} = \frac{1}{V_t} J_S A E \left. e^{\frac{V_{BE}}{V_t}} \right|_{V = V_o} = \frac{I_{BQ}}{V_t} \approx \frac{I_{CQ}}{\beta V_t}
\]

\[
y_{21} = g_m = \left. \frac{\partial I_C}{\partial V_{BE}} \right|_{V = V_o} = \frac{1}{V_t} J_S A E \left. \left(1 + \frac{V_{CE}}{V_{AF}}\right) \right|_{V = V_o} = \frac{I_{CQ}}{V_t}
\]

\[
y_{12} = \left. \frac{\partial I_B}{\partial V_{CE}} \right|_{V = V_o} = 0
\]

\[
y_{22} = g_o = \left. \frac{\partial I_C}{\partial V_{CE}} \right|_{V = V_o} = \frac{J_S A E}{V_{AF}} \left. \frac{V_{BE}}{V_t} \right|_{V = V_o} \approx \frac{I_{CQ}}{V_{AF}}
\]

Note: usually prefer to express in terms of \( I_{CQ} \)
Small Signal Model of BJT

\[ i_B = y_{11} V_{BE} + y_{12} V_{CE} \]
\[ i_C = y_{21} V_{BE} + y_{22} V_{CE} \]

\[ g_\pi = \frac{I_{CQ}}{\beta V_t} \]
\[ g_m = \frac{I_{CQ}}{V_t} \]
\[ g_o = \frac{I_{CQ}}{V_{AF}} \]

An equivalent circuit

y-parameter model using “g” parameter notation
Consider again:

Small signal analysis example

\[ V_{IN} = V_M \sin \omega t \]

Recall the derivation was very tedious and time consuming!

\[ A_{VB} = -\frac{I_{CO} R}{V_t} \]

Derived for \( V_{AF} = 0 \)
Neglect $V_{AF}$ effects (i.e. $V_{AF}=\infty$) to be consistent with earlier analysis

$$g_o = \frac{I_{CQ}}{V_{AF}} = 0$$

$$V_{OUT} = -g_m R V_{BE}$$

$$V_{IN} = V_{BE}$$

$$A_v = \frac{V_{OUT}}{V_{IN}} = -g_m R$$

$$g_m = \frac{I_{CQ}}{V_t}$$

$$A_v = -\frac{I_{CQ} R}{V_t}$$

Note this is identical to what was obtained with the direct nonlinear analysis
Small Signal BJT Model – alternate representation

$g_m = \frac{I_{CQ}}{V_t}$

$g_\pi = \frac{I_{CQ}}{\beta V_t}$

$g_o \approx \frac{I_{CQ}}{V_{AF}}$

Observe:

$g_\pi v_{be} = i_b$

$g_m v_{be} = i_b \frac{g_m}{g_\pi}$

$g_m = \frac{I_Q}{V_t}$

$g_\pi = \frac{I_Q}{\beta V_t}$

$\beta = \frac{I_Q}{\beta V_t}$

$g_m v_{be} = \beta i_b$

Can replace the voltage dependent current source with a current dependent current source
Small Signal BJT Model – alternate representation

\[ g_m = \frac{I_{CQ}}{V_t} \]
\[ g_\pi = \frac{I_{CQ}}{\beta V_t} \]
\[ g_o \approx \frac{I_{CQ}}{V_{AF}} \]

Alternate equivalent small signal model

\[ g_\pi = \frac{I_{CQ}}{\beta V_t} \]
\[ g_o \approx \frac{I_{CQ}}{V_{AF}} \]
Small-Signal Model Representations

(3-terminal network – also relevant with 4-terminal networks)

- Have developed small-signal models for the MOSFET and BJT

- Models have been based upon arbitrary assumption that $v_1, v_2$ are independent variables

- Models are y-parameter models expressed in terms of “g” parameters

- Have already seen some alternatives for “parameter” definitions in these models

- Alternative representations are sometimes used
Small-Signal Model Representations

The good, the bad, and the unnecessary!!

what we have developed:

The hybrid parameters:

Independent parameters
Small-Signal Model Representations

The z-parameters

\[ V_1 = z_{11} i_1 + z_{12} i_2 \]
\[ V_2 = z_{21} i_1 + z_{22} i_2 \]

The ABCD parameters:

\[ V_1 = A v_2 - B i_2 \]
\[ i_1 = C v_2 - D i_2 \]
Small-Signal Model Representations

Amplifier parameters

\[ V_1 = R_{IN} i_1 + A_{VR} v_2 \]
\[ V_2 = R_{OUT} i_2 + A_V v_1 \]

• Alternate two-port characterization but not expressed in terms of independent and dependent parameters

• Widely used notation when designing amplifiers
Small-Signal Model Representations

The S-parameters

(embedded with source and load impedances)

The T parameters:

(embedded with source and load impedances)
Small-Signal Model Representations

- Equivalece circuits often given for each representation
- All provide identical characterization
- Easy to move from any one to another

The good, the bad, and the unnecessary!!
Small-Signal Model Representations

The good, the bad, and the unnecessary!!

IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 42, NO. 2, FEBRUARY 1994

Conversions Between $S$, $Z$, $Y$, $h$, $ABCD$, and $T$ Parameters which are Valid for Complex Source and Load Impedances

Conversions between $S$, $Z$, $Y$, $H$, $ABCD$, and $T$ parameters which are valid for complex source and load impedances

DA Frickey - IEEE Transactions on microwave theory and ..., 1994 - ieeexplore.ieee.org
This paper provides tables which contain the conversion between the various common two-port parameters, $Z$, $Y$, $H$, $ABCD$, $S$, and $T$. The conversions are valid for complex normalizing impedances. An example is provided which verifies the conversions to and from $S$

Cited by 370 Related articles All 5 versions

As of Mar 6, 2018
Small-Signal Model Representations

The good, the bad, and the unnecessary!!

Conversions Between $S$, $Z$, $Y$, $h$, $ABCD$, and $T$ Parameters which are Valid for Complex Source and Load Impedances

Dean A. Frickey, Member, IEEE
Small-Signal Model Representations

The good, the bad, and the unnecessary!!

Conversions Between $S$, $Z$, $Y$, $h$, $ABCD$, and $T$ Parameters which are Valid for Complex Source and Load Impedances

Dean A. Frickey, Member, IEEE
What are the simplified dc equivalent models?
Active Device Model Summary

What are the simplified dc equivalent models?

dc equivalent

\[ V_{GSQ} \left( \frac{\mu C_{OX} W}{2L} \right) (V_{GSQ} - V_{Tn})^2 \]

\[ V_{GSQ} \left( \frac{\mu C_{OX} W}{2L} \right) (V_{GSQ} - V_{Tp})^2 \]
Small-signal Operation of Nonlinear Circuits

- Small-signal principles
- Example Circuit
- Small-Signal Models

Small-Signal Analysis of Nonlinear Circuits
Recall:

Alternative Approach to small-signal analysis of nonlinear networks

1. Linearize nonlinear devices
   *(have small-signal model for key devices!)*

2. Replace all devices with small-signal equivalent

3. Solve linear small-signal network

Remember that the small-signal model is operating point dependent!

Thus need Q-point to obtain values for small signal parameters
End of Lecture 25